Data-driven Modeling, Prediction and Predictability:
The Complex Systems Framework

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Nonlinear Dynamics and Complexity

Dynamics (Lorenz, 1963)

- Deterministic dynamics, Chaos
- Quantitative results
- Weak connection with data

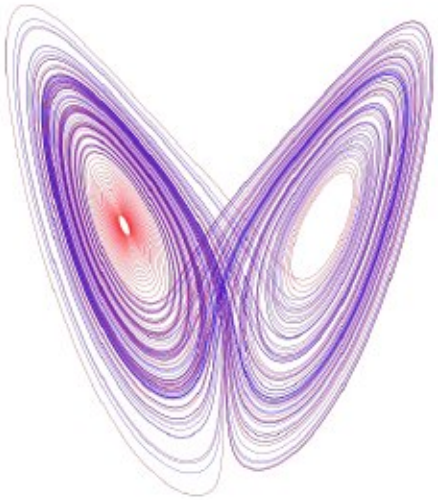
Structure (Mandelbrot, 1977)

- Real objects in nature
  - (Trees, clouds, coastline, etc.)
- Fractals and Multifractals

Dynamics + Structure

- Spatio-temporal Dynamics
- Data-driven modeling in Complex Systems Framework

Machine Learnimg / Artificial Intelligence



Reconstruction of Dynamics

"Geometry from a time series"

(Packard et al., 1980)

Embedding theorem (Takens, 1981)

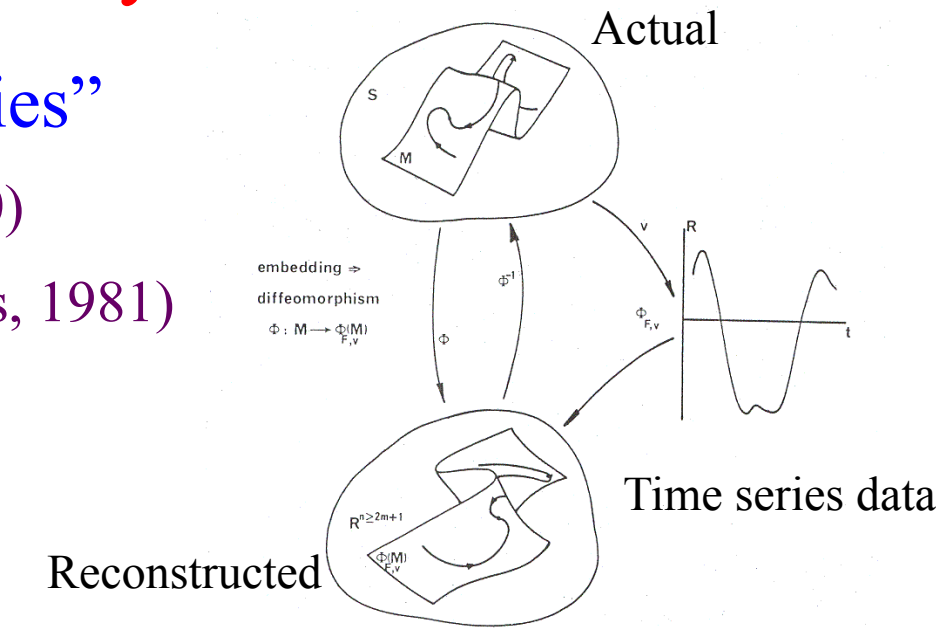
Time series data: $x(t)$

Time-delay embedding:

$$x_k(t_i) = x(t_i + (k\text{-}1)\tau)$$

Reconstructed space:

$$X_i = \{x_1(t_i), x_2(t_i), x_3(t_i), ..\}$$



(Broomhead and King, J. Phys. A, 1986)

Complex Systems Framework:

- Low-dimensional (data-driven) modeling
- Dynamical prediction (Dynamics)
- Predictability analysis (Statistics)

Space Weather:
Prediction and Predictability

Data-driven Modeling:

Phase space reconstruction of driver (solar wind) – response (magnetosphere)

- Storms (Dst)
- Substorms (AL)
- Killer electron flux

First Predictions

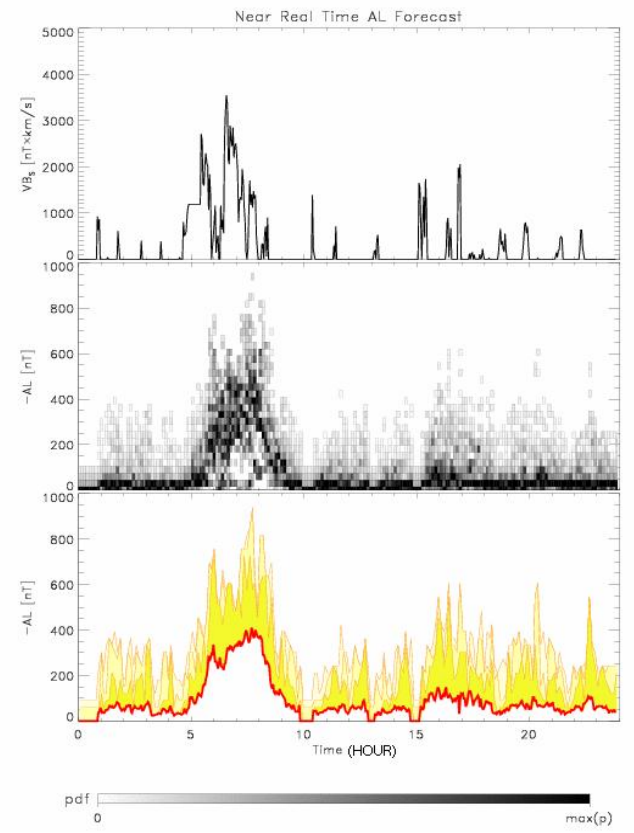
[Sharma, Rev. Geophys., 1995]

Early contributions to AI / Machine Learning

Solar wind (VBs)

Past data: auroral electrojet index AL

Predicted AL and Predictability



[*Ukhorskiy et al.*, 2002, 2004].

Predictability of Space Weather

Global or Coherent aspects of the Magnetosphere

Demonstrated by

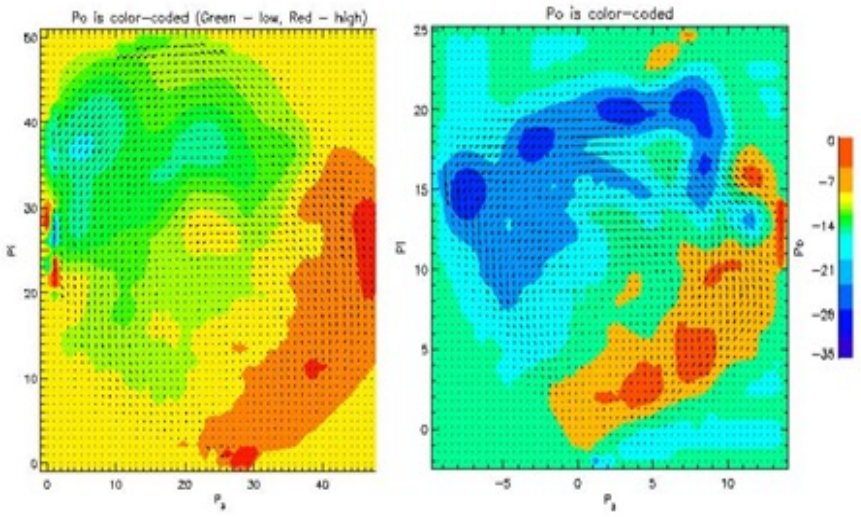
- Low-dimensionality – reconstruction of phase space [Vassiliadis et al., 1990; Sharma et al., 1993]
- Modeling [Baker et al., 1990]
- Phenomenology [Siscoe, 1991]
- Phase transition-like behavior from data-driven modeling and MHD simulations

implies Predictability

Fundamental contribution based on data-driven modeling
(AI / Machine Learning)

Similar to early results on dynamical behavior of the atmosphere

Magnetospheric Transitions:
Phase Transition-like Behavior



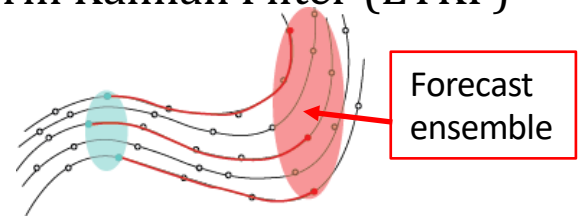
From vBs-AL Index Data
Sitnov et al., JGR, 2000; Phys. Rev. E, 2001.

From vBs-**Pseudo** AL Index: Global MHD simulations
Shao et al., JGR, 2003

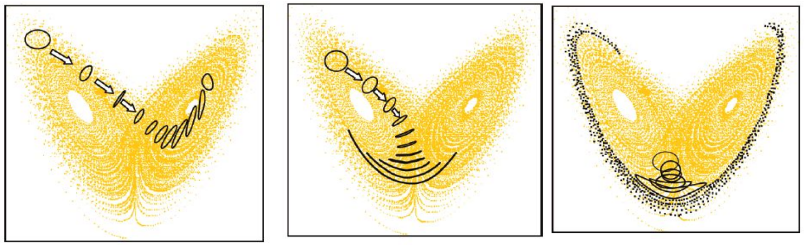
Transition from higher (orange) to lower (green) level.
AL index data – observed and from global MHD simulations.

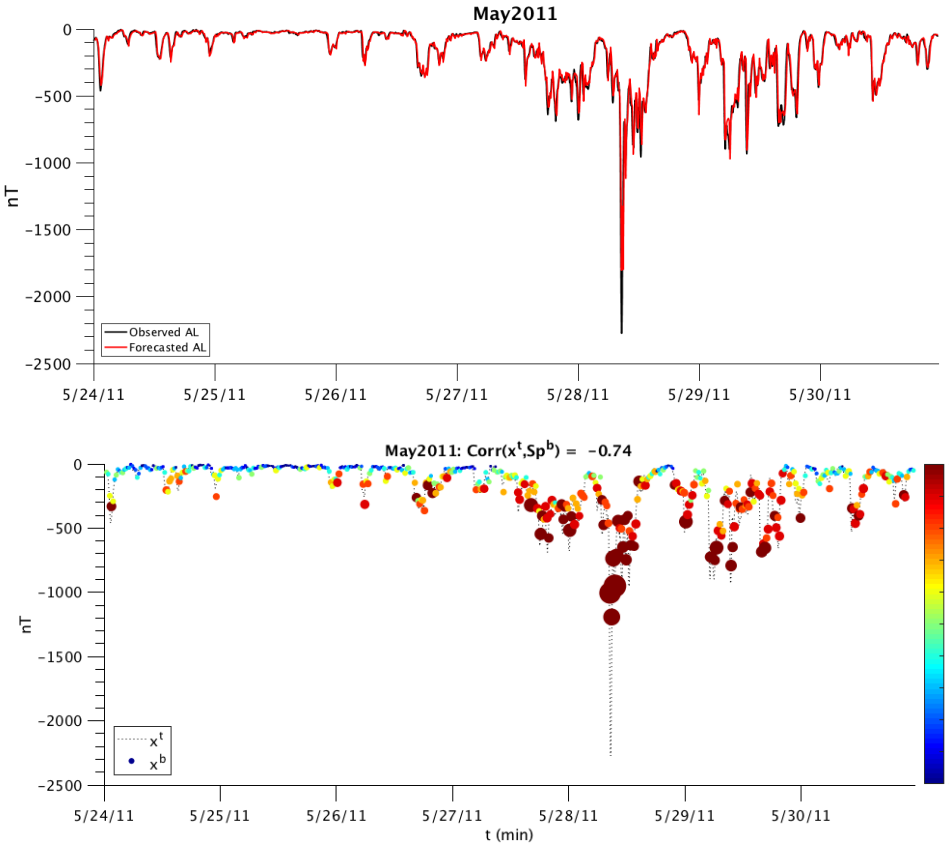
Extreme events and Ensemble forecasting

- Data-driven models without governing equations
- Forecasts using Ensemble Transform Kalman Filter (ETKF)



- Ensemble spread as an indicator of extreme events





Erin Lynch, Ph. D. thesis (2018)

Data-driven Prediction of Monsoon

Phase space reconstruction model (PSRM).

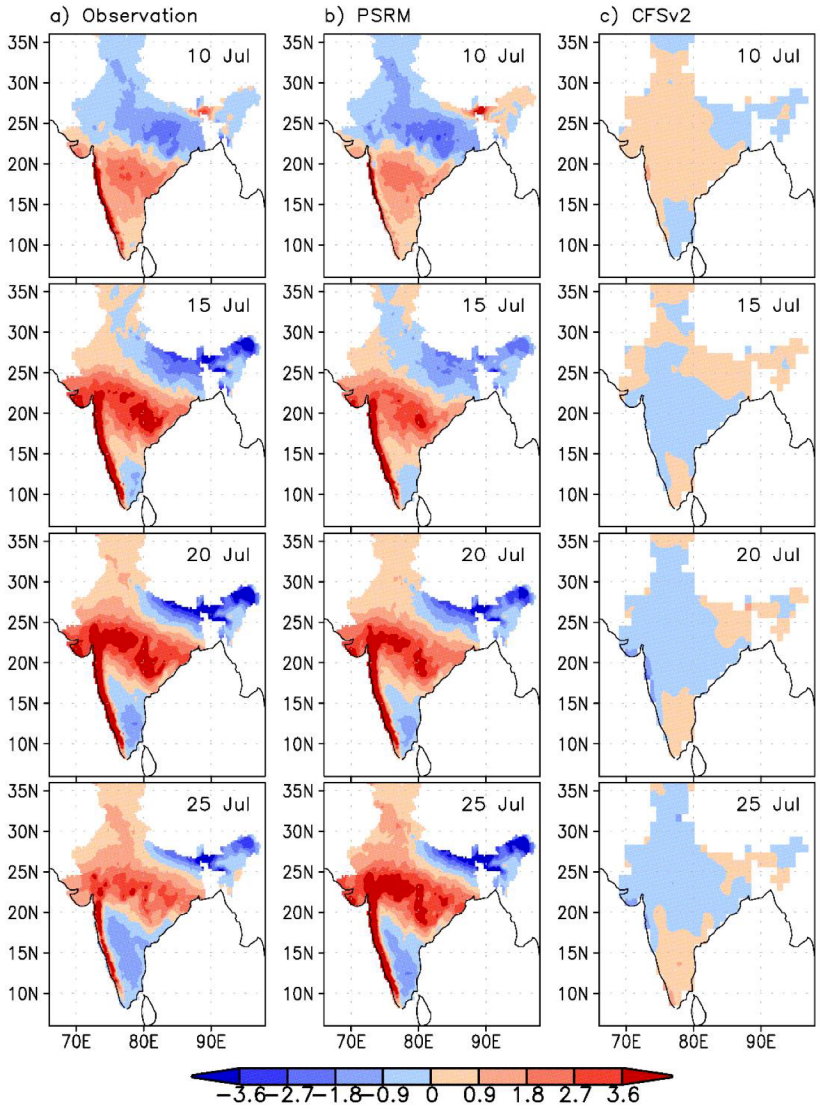
Rainfall data on 0.25 deg longitude × 0.25 deg latitude grid for 1901-2009 (1800 stations)

Climate Forecasting System (CFSv2)
State of the art numerical model (NOAA)

Modeling by Reconstruction using Rainfall and CFSv2 data.

Improvement of predictability

Krishnamurthy and Sharma, Geophys. Res. Lett. (2017)



Comparison of predictions of PSRM and CFSv2

Key results and conclusions:

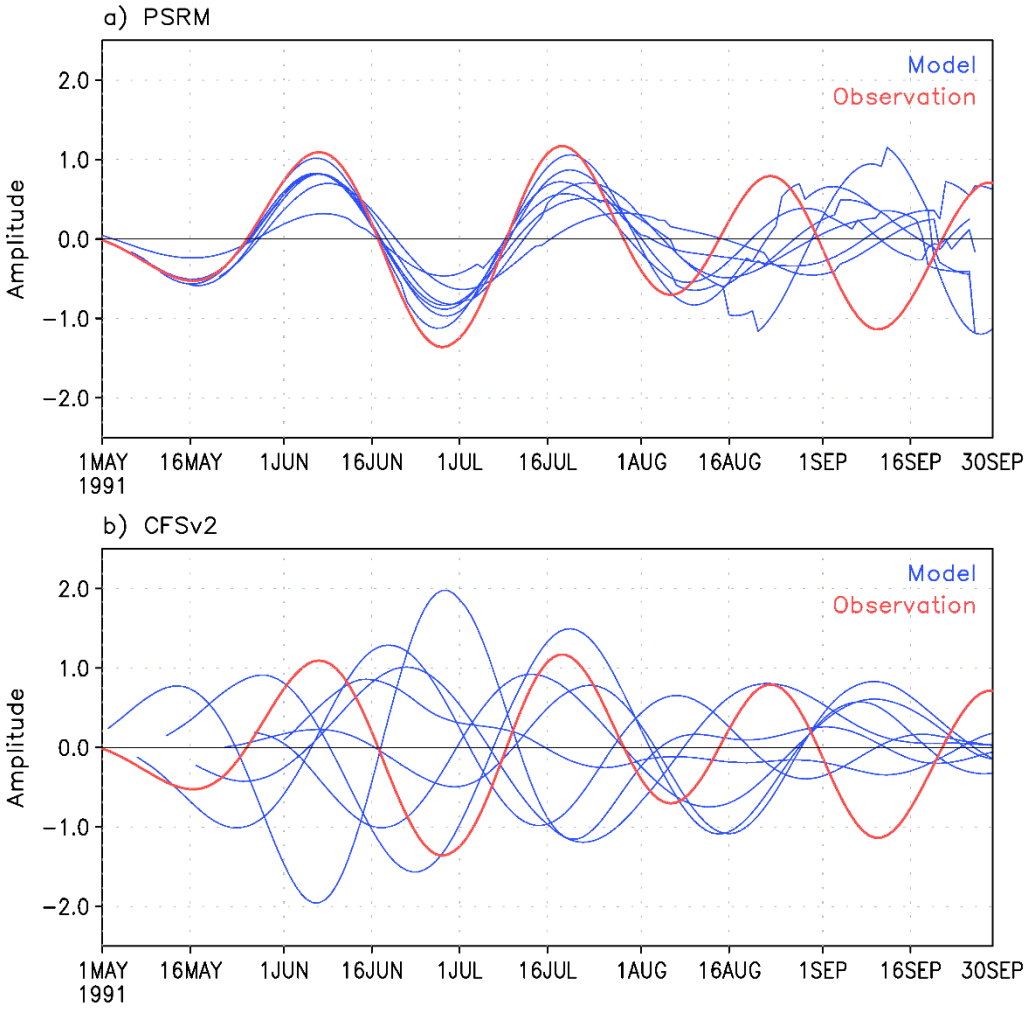
Intraseasonal oscillations are predictable

Predictability of intraseasonal phenomena such as MJO and midlatude processes

Data-driven modeling provides higher predictability

Modeling and prediction of spatio-temporal structure of space weather

Spatio-temporal Data: Networks of monitoring stations



Krishnamurthy and Sharma, Geophys. Res. Lett., 2017

Complex Systems Framework

- Data-driven Modeling
- Dynamical prediction (global and spatially extended)
- Characterization of predictability
- Extreme events: Quantification of predictability
- Predictability of **extreme events from Big Data**
- Quantitative measure of the **likelihood of extreme space weather** events (data-driven modeling)
- **Prediction of Intraseasonal climate (Indian Monsoon)**
- Applications and a framework for **artificial intelligence,** and **machine learning**
- Fourth paradigm – Data –enabled science